UTILIZATION OF THE IR TELESCOPE GIMBALING SYSTEM AS A STABILIZED POINTING PLATFORM FOR BALLOON PAYLOADS

Contract NAS8-37579
Final Report

For the Period 4 February 1988 through 3 May 1988

FEASIBILITY STUDY

Volume I: Technical Results

Principal Investigator
Mr. George U. Nystrom

MAY, 1988

Prepared for
National Aeronautics and Space Administration
Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

Submitted by
Smithsonian Institution
Astrophysical Observatory
Cambridge, Massachusetts 02138

The Smithsonian Astrophysical Observatory
is a member of the
Harvard-Smithsonian Center for Astrophysics

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STUDY REPORT

ANNOTATED VIEW-GRAPHS

This submission is prepared in response to the MSFC Statement of Work for a feasibility study entitled "Utilization of the IR Telescope Gimbaling System as a Stabilized Pointing PLatform for Balloon Payloads." In response to that statement of work, SAO examined existing designs for the One-Meter IR and EXITE Telescope gimbal systems and gondolas for possible application to the GRID experiment, which has considerably more stringent pointing requirements. In response to the task statement we traded the existing designs against alternatives using a strawman gondola concept, examining both performance and survivability. Because the SAO designs had, in effect, already incorporated such trades when originally developed, and because they already accommodate a heavy experiment package, the principal modifications required arose from the need for better torque noise performance. We identified the need for better bearinigs and torquers and the piece-part redesign to incorporate them, along with newly designed electronics. We then developed a program plan, WBS, and cost estimate to provide such a gimbal system and control/interface electronics.

We have chosen a gimbal configuration with the azimuth drive between the suspension ladder and the gondola, and the elevation drive at the telescope. This simple, low weight arrangement takes maximum advantage of existing, proven SAO designs and is well-protected from landing impact. Other locations for the azimuth drive, or a cross-elevation configuration, were also examined, but have comparative weight penalties and offer no other advantages except freedom from gimbal lock in near-zenith viewing.

One potential disadvantage of the overhead azimuth drive is that gondola flexibility could introduce control loop problems. Our strawman gondola concept developed for this study showed that we could achieve sufficient stiffness to meet pointing requirements and still maintain the low weight necessary to permit operation with the relatively massive GRID experiment. The strawman concept was carried far enough that we could estimate mass properties, but the structure has not been optimized, and further trades are necessary during the design phase.

To be responsive to the statement of work for the study, a cost estimate for the gondola is not included. However, it should be noted that separating gondola design and fabrication from that for the gimbal adds redundant costs to both. This is true both for hardware such as support fixtures and test electronics and for study items such as structural analysis. It also makes verification difficult at the subassembly stage. SAO experience indicates that designing and fabricating the gondola and pointing systems together ensures that system problems are identified and eliminated at the earliest possible stage, and that duplication of effort is avoided. SAO could provide an additional estimate for design/fabrication of the gondola along with the gimbal system if desired.

We have included costs for redesign of the gimbal servo electronics. Existing designs reflect old technology and would not be desirable for the modified gimbals. New design will give considerably greater flexibility in setting control loop dynamics during systems test, even in changing loop dynamics for future flights with a modified experiment package. We also have included interface circuits with pointing and aspect sensors and the telemetry systems. The sensors themselves are not included to allow the government maximum flexibility in source of supply. We also assume that all electronics will serve for both bench and systems test and for flight, and will be packaged accordingly.

For interface verification and integration/test support at MSFC we have assumed a total of five engineers for ten weeks. This includes all activities for interface verification, integration with gondola and experiment, and full systems tests. This should be interpreted as a costing assumption only since no scope of work has been defined for the necessary support.

This package includes all deliverables specified in the Statement of Work:

- a program schedule for a gimbal system for GRID
- a WBS and cost estimate for the gimbal system
- gimbal design layouts from the EXITE, which form the basis for the GRID gimbal
- a preliminary layout of the strawman gondola showing the gimbal interfaces
- a study report in annotated view-graph format incorporating all study results.

GRID GIMBAL SYSTEM
DESIGN OVERVIEW

■ The GRID gimbal system presented here is based on SAO's experience designing successful pointed experiments on scientific balloon programs such as:

» the 1-meter IR telescope

» the Fourier Infrared Spectrometer (FIRS)

» the Energetic X-ray Imaging and Timing Experiment (EXITE)

■ Our approach in this study was to evaluate gimbal designs developed for both the EXITE and 1-meter instruments against the requirements for the GRID experiment. The EXITE design was chosen as a basis for further study because it is a more recent design and incorporates a number of improvements over the 1-meter gimbal.

■ To meet the stated GRID pointing requirements, the present EXITE gimbal design requires modification to include brushless torque motors and higher quality bearings. These changes reduce the estimated torque disturbances by a factor of 17 in elevation and a factor of 11 in azimuth. Additional side benefits of the modified design are: simpler mechanical design, lower parts count, and easier maintenance in the field.

■ Weight requirements for the GRID application demand an extremely light weight supporting gondola. We developed a "strawman" gondola design to support the gimbal study which shows that the stiffness and damping characteristics of this gondola structure are a major factor in total payload system performance. A detailed study of the final gondola structure is necessary to optimize servo loop performance and to ensure that the gimbal and gondola together meet the pointing and stability requirements of the GRID mission.

GRID GIMBAL SYSTEM
DESIGN OVERVIEW

The SAO gimbal concept for the GRID experiment:

- is based on our previous experience with pointed balloon-borne instruments
- is a modified version of our present EXITE gimbal
- uses upgraded components to reduce torque disturbance below EXITE by a factor of 17 in elevation, 11 in azimuth
- meets all of the stated pointing requirements for the GRID mission, when mounted on a gondola possessing suitable structural properties

GRID POINTING CONTROL STABILITY REQUIREMENTS

The most demanding limitations on pointing jitter is that of image smear. Based on the assumption that the solar sensor will provide aspect information every ten milliseconds, the telescope short-term stability must be no worse than 0.2 arcsec (rms) in ten milliseconds, or 20 arcsec/sec in both Elevation and Azimuth. I.e., over some portion of the error frequency spectrum, we require the pointing system to be velocity limited.

As the error frequency increases, maximum allowable error velocity is reached with a smaller peak excursion, until at a frequency of 17 Hz an excursion of 0.2 arcsec rms results in a velocity of 33 arcsec/sec, peak. Above this frequency, it is only necessary to limit excursions to 0.2 arcsec rms, regardless of frequency -- an amplitude limited situation.

At very low frequencies, we are limited by the requirements that the maximum deviation of the GRID instrument optical axis from the sun-center line must be less than three arcminutes. In other words, if the frequency is low enough, it is possible to exceed the maximum allowable excursion while remaining within the stated velocity requirements. This defines another amplitude limited region, below 0.03 Hz, where the peak deviation must be below three arcminutes.

GRID POINTING CONTROL STABILITY REQUIREMENTS

Stated requirements -- Azimuth and Elevation

- Pointing error less than 0.2 arcseconds rms over any 10 millisecond interval
- Maximum pointing error less than three arcminutes

These requirements can be translated into the following frequency-domain specifications on pointing jitter:

- At all frequencies above 17 Hz, jitter amplitude must be less than 0.2 arcseconds rms
- Between 0.03 Hz and 17 Hz, jitter velocity must be less than 33 arcseconds/second
- Below 0.03 Hz, jitter amplitude must be below 3 arcminutes peak

Stated requirements -- Roll

- 0.7 arcminutes over any 10 millisecond interval
- Absolute roll orientation -- no stated requirements

GRID GIMBAL LAYOUT

The EXITE design, an azimuth gimbal at the connecting point of the gondola to the shroud lines and an inner gimbal at the mounting point of the telescope, was selected as a basis for the GRID design since only minor changes are required. By placing the azimuth gimbal at the top of the structure (as opposed to a bottom-mounted gimbal) and by not including a second inner gimbal for cross-elevation a significant weight savings is realized.

The disadvantages of this arrangement are:

- Azimuth telescope pointing is affected by gondola structural dynamics, and requires a gondola structure stiff enough to remove any dynamics from a range that would affect pointing. The strawman design has shown that this is possible.
- Telescope pointing precision degrades at high elevation angles as the system approaches gimbal lock.

Gondola structural dynamics affects pointing because the entire structure is between the point where the telescope position is measured and where the torque motor acts to correct azimuth position. The only way to remove these dynamics from the loop is to move the azimuth gimbal closer to the telescope. This could be accomplished either by placing, 1) an azimuth gimbal at the bottom of the telescope or, 2) a cross-elevation gimbal ring at the telescope mounting axis.

The first approach requires a telescope mounting fork and resembles modern telescope mounting systems such as the Multiple Mirror Telescope. This arrangement results in a large weight increase and does not address the gimbal lock problem. The second approach brings the gimbal much closer to the telescope and eliminates gimbal lock completely. We discuss this approach more completely later in this presentation.

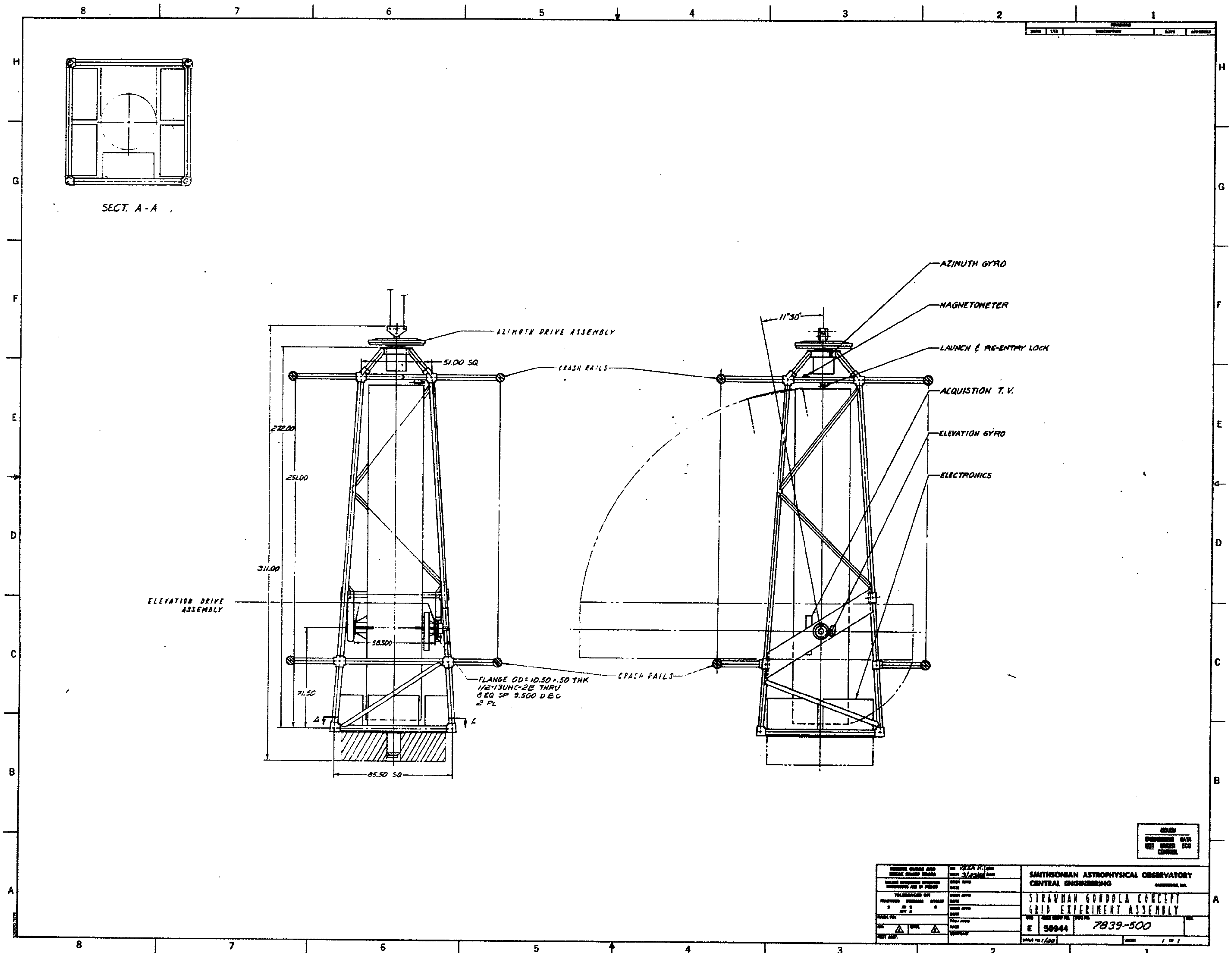
The mechanical interfaces between the telescope and the elevation gimbal, and between the upper gondola and the azimuth gimbal are shown here and can be seen in more detail in the full sized SAO drawings 7839-501 and 7080-505 (included with this report). The elevation gimbals each present two bolt circles, one for attaching to the telescope and the other to the gondola. The azimuth gimbal is fastened to the top of the gondola by a bolt circle and is pinned to the suspension ladder.

GRID GIMBAL LAYOUT

The gimbal arrangement used in the EXITE gondola was selected as a basis for the GRID design.

Major features of this design are:

- Single azimuth bearing at the top of the gondola
- Elevation gimbal at the telescope mount
- No inner (cross-elevation) gimbal


SECT. A-A
AZIMUTH DRIVE ASSEMBLY
51.00 SQ
CRASH RAILS
272.00
251.00
311.00
ELEVATION DRIVE ASSEMBLY
58.500
71.50
FLANGE OD=10.50 ×.50 THK
1/2-13UNC-2B THRU
8 EQ SP 9.500 D B C
2 PL
85.50 SQ
11°30'
AZIMUTH GYRO
MAGNETOMETER
LAUNCH & RE-ENTRY LOCK
ACQUISTION T.V.
ELEVATION GYRO
ELECTRONICS
CRASH RAILS
ENGINEERING DATA NOT UNDER ECO CONTROL
VESA K.
SMITHSONIAN ASTROPHYSICAL OBSERVATORY
CENTRAL ENGINEERING
STRAWMAN GONDOLA CONCEPT
GRID EXPERIMENT ASSEMBLY
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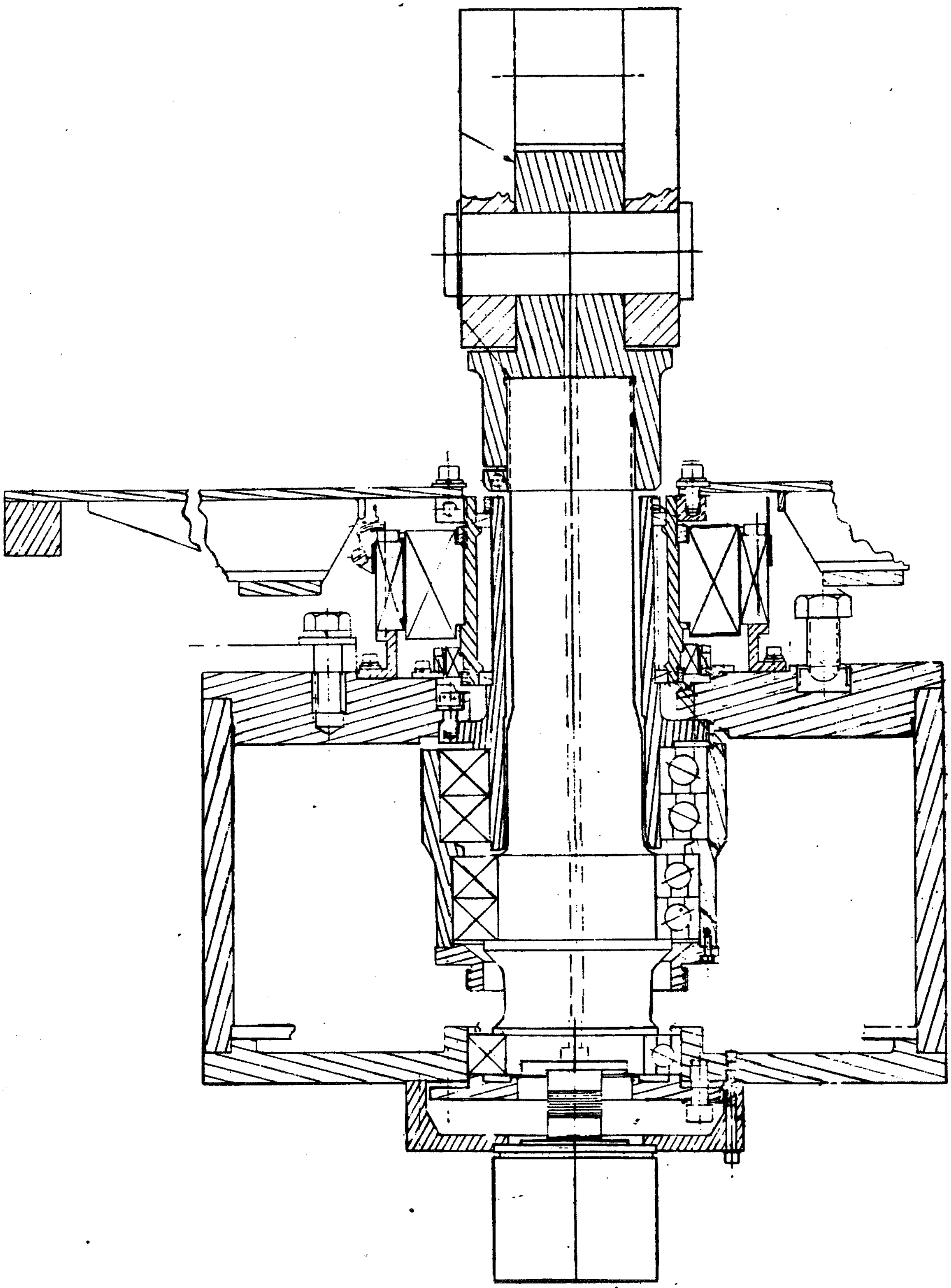
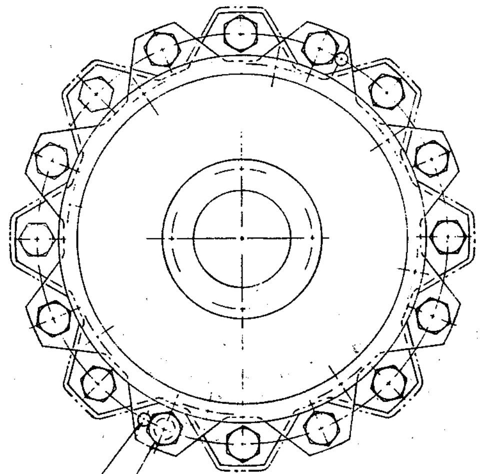
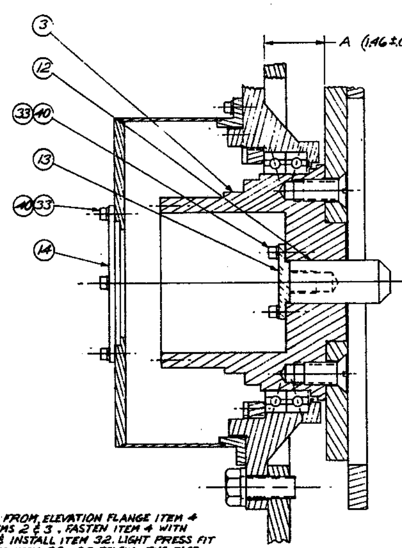
1/40
1 OF 1

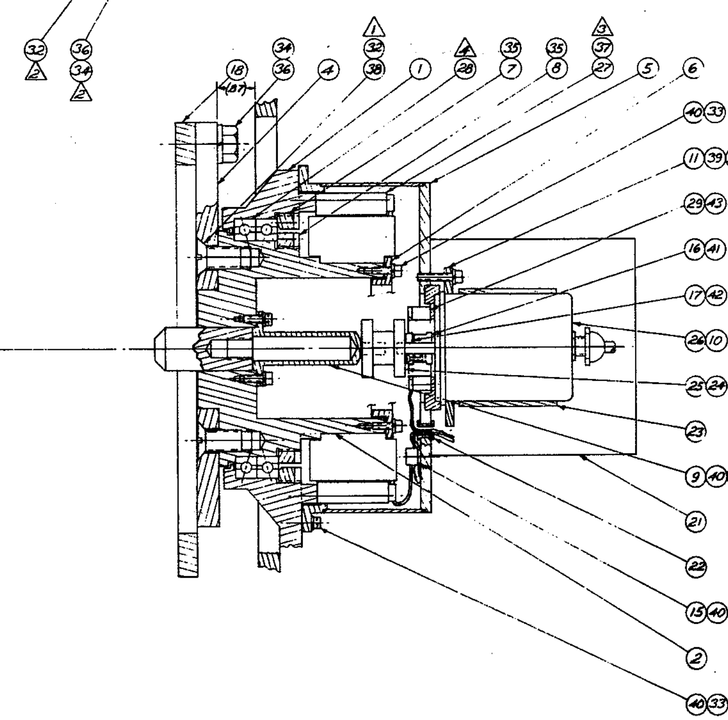


PROPOSED AZIMUTH
DRIVE ASS'Y
GRID

REVISIONS				
ZONE	LTR	DESCRIPTION	DATE	APPROVED







1. TRANSFER HOLE PATTERN FROM ELEVATION FLANGE ITEM 4 TO ELEVATION HUBS ITEMS 2 & 3. FASTEN ITEM 4 WITH ITEMS 38. DRILL, REAM & INSTALL ITEM 32. LIGHT PRESS FIT TO FLANGE & HUB. PRESS ITEM 32 .03 PELOW THE FACE OF THE FLANGE ITEM 4.

2. ASSEMBLING ELEVATION DRIVE TO GONDOLA. SLIDE ACCURACY ROUND ITEM 31 THRU 1.000 DIA HOLES OF RIGHT & LEFT SIDE ASSEMBLYS TO DETERMINE CONCENTRICITY & PERPENDCULARITY. USE METAL SHIMS AS REQUIRED BOTH SIDES BETWEEN GONDOLA FACE & ELEVATION BEARING HOUSING ITEM 1 TO OBTAIN AXIAL DISTANCE BETWEEN FLANGES ITEM 4 (TO MATCH DETECTOR WIDTH). DIMENSION A TO BE .96±.06, & PERPENTICULARITY OF BEARING HOUSINGS ITEM 1. TIGHTEN SCEWS ITEM 36. DRILL, REAM & INSTALL 2 DOWEL PINS ITEM 32 TO BOTH SIDES LOCATING BEARING HOUSING ITEM 1 TO GONDOLA. PRESS FIT TO GONDOLA & SLIP FIT TO BEARING HOUSING ITEM 1. IF AXIAL DISTANCE NEED TO BE READJUSTED AFTER INSTALLING DETECTOR ASSY TO OBTAIN CORRECT A DIMENSION, CARE MUST BE TAKEN TO MAINTAIN BEARING HOUSING ITEM 1 ORIENTATION & CONCENTRICITY.

3. INSTALLING MOTOR ITEM 27. AFTER ASSEMBLING DETECTOR ASS'Y & BEARING ASSEMBLYS SLIDE ROTOR INTO HUB-RIGHT SIDE & SECURE IN PLACE WITH ROTOR RETAINER ITEM 6 & SCREWS ITEM 33. INSTALL STATOR & ADJUST IT TO BE CONCENTRIC WITH ROTOR USING SHIMS. CHECK CONCENTRICITY WITH CHIMS ALL THE WAY AROUND WHILE ROTATING ELEVATION DRIVE OVER ENTIRE RANGE.

4. DUBLEX BEARING TO BE ASSEMBLED FACE TO FACE AS THEY ARE FACTORY GROUND FOR PROPER PRELOAD.

QTY	ITEM OR FIND NO.	DWG SIZE		PART NO. OR IDENTIFYING NO.	DESCRIPTION
4	43			MATL: SST	SCREW FLAT HD. 2-56UNC-2A×.375 LG
4	42			MATL: SST	SCREW FLAT HD. 2-56UNC-2A×.31 LG
1	41			DY1107	SET SCREW, ADCO
36	40			MATL: SST	SCREW SCH. 8-32UNC-2A×.50 LG.
4	39			MATL: SST	SCREW SCH. 8-32UNC-2A×.87 LG.
8	38			MATL: SST	SCREW FLAT HD. 1/2-13UNC-2A×1.00 LG
4	37			MATL: SST	SCREW FLAT HD. 6-32UNC-2A×1.87 LG
32	36			MATL: SST	SCREW HEX HD. 1/2-13UNC-2A×1.25 LG.
3	35			DCS26	SET SCREW, ADCO
32	34			MATL: SST	LOCK WASHER 1/2
38	33			MATL: SST	LOCK WASHER NO. 8
6	32			DL2D875	DOWEL PIN ADCO
REF	31			[illegible] LG	ACCURACY ROUND, RYERSON
	30				
1	29			QT6-1303	TACHOMETER, INLAND MOTOR
2	28			KD050FR0A	BEARING, KAYDON 2 DUPLEXES
1	27			QT-6206-D	MOTOR, INLAND MOTOR
1	26			SERIES M-25	LED OPTICAL ENCODER, BEI ELECTRONICS
1	25			W3-CS	COUPLING, METAL BELLOWS COR.
2	24			GC-15-5	CLAMP, METAL BELLOWS COR.
1	23				HEATER
1	22			2552	GROMMET, ATLANTIC INDIA RUBBER
AR	21				INSULATION, CLOSE CELL POLYURETANE
	20				
	19				
2	18			MATL: AL	SPACER 10.50 OD×8.50 ID×.434 THK
1	17			7080-1139	TACHOMETER RETAINER
1	16			-1138	TACHOMETER SPACER
2	15	B		-1033	CABLE CLAMP
1	14	B		-1011	ELEVATION DR. COVER PLATE
1	13	B		-1010	PIN RETAINER
2	12	B		-1009	ELEVATION PIN
1	11	B		-1008	ENCODER RETAINER
1	10	B		-1137	TACHOMETER & ENCODER INSULATOR
1	9	B		-1006	ENCODER SHAFT
1	8	C		-1005	BEARING NUT - INNER
2	7	C		-1004	BEARING NUT - OUTER
1	6	C		-1003	ROTOR RETAINER
2	5	D		-1002	ELEVATION DRIVE COVER
2	4	E		-1001-3	ELEVATION FLANGE
1	3	E		-1001-2	ELEVATION HUB - LEFT
1	2	E		-1001-1	ELEVATION HUB - RIGHT
2	1	E		7080-1000	ELEVATION BEARING HOUSING

PARTS LIST

ISSUED
ENGINEERING DATA NOT UNDER ECO CONTROL

NEXT ASSY | USED ON
APPLICATION

DR VESA K. DATE 11/21/84

SMITHSONIAN ASTROPHYSICAL OBSERVATORY CAMBRIDGE, MA.

TITLE: PROPOSED ELEVATION DRIVE ASS'Y GRID

SIZE E | 50944

SCALE 1/2 | SHEET 1 OF 1

REQUIRED MODIFICATION TO EXITE DESIGN

Once the EXITE design was selected it was clear that the torque disturbances created by the ball bearings, the brush-type torque motors and the momentum dump system were too great to allow the system to meet the stated GRID pointing specifications. Thus we propose that higher-quality ball bearings, selected for low friction, be used in the GRID gimbal and that the torque motors in both axes be replaced by brushless motors, completely eliminating brush ring friction as a source of disturbance. These two changes -- along with minor redesign of some other existing parts -- reduce the torque noise in the gimbals by a factor of 5 and the startup torque by a factor of 10, compared with EXITE.

The proposed GRID momentum dump method is different from that used on EXITE in that a brushless torque motor is directly coupled between the shroud lines and the gondola, replacing the present arrangement of a dither motor, dither wheel and rolling connection to the shroud lines. This improved design takes advantage of recent advances in bearing technology and the availability of brushless torque motors, which were either not available at the time of the original 1-meter and EXITE system development or were prohibitively expensive.

This approach reduces the number of parts in the momentum dump assembly, simplifies its design and results in cleaner and more predictable operation. In addition, eliminating the dither motor removes another source of torque disturbance from the azimuth axis.

SAO design concept -- GRID gimbal

REQUIRED MODIFICATION TO EXITE DESIGN

Elevation gimbal:

Requires minor redesign of:

1) Elevation Flange
2) Encoder Shaft
3) Elevation Drive Cover

Azimuth Gimbal:

Requires design modification of:

1) Bearing housing
2) Bearing sleeve
3) Stator Mount
4) Reaction Wheel

Momentum dump system:

1) Six parts are removed and the design of two others is simplified.

2) A brushless torque motor is added.

POINTING DISTURBANCES

After modifying the basic EXITE gimbal design as described on page 5 of this report, the new background disturbance torque was estimated by considering three categories :

1) break-free torque, or that torque required to initiate rotation about an axis,

2) constant running torque, or the "dc" component of the torque required to maintain rotation, and

3) varying running torque, or the "ac" component of the the torque felt on a rotating axis (torque noise).

Individual identifiable sources in each of these categories were estimated and the net results entered in the table on the next page -- straight sum for break-free torque and root-sum-square for varying running torque. Values are given for the azimuth axis only, since we expect the worst-case performance in that axis, and that is where we did most of the pointing performance simulation.

The break-free torque levels for the two axes were determined based on the respective vendors' specifications. The constant levels were assumed to be half of break-free torque for ball bearings and equal to break-free torque for motors. Varying levels were assumed to be 25% of the constant running levels, a value that has proved to be conservative in SAO experiences.

Break-free torque was used to simulate start up transients and the effect of gondola pendulum on the payload pointing. Varying torque was used to determine the pointing errors in the slewing system. Constant running torque was used only to size the motors.

An additional noise source, not shown in the table, is cross-coupled torque from the azimuth axis into the elevation axis. At elevation angles above the horizontal the centrifugal force caused by azimuth rotation will result in a torque about the elevation axis. This is of the order of 0.05 Nm at 30 degrees of elevation and falls off rapidly on either side.

SAO design concept -- GRID gimbal

POINTING DISTURBANCES

Gyro disturbances

- Gyro drift -- steady-state component is removed by the integration designed into the outer (solar sensor) loop
- Gyro noise -- less than 0.02 arcsec rms in a bandwidth of 0.5 Hz

Azimuth torque disturbances, running

■ Torque motor cogging	0.03 Nm (rms)
■ Reaction wheel rumble	0.02 Nm
■ Bearing noise	0.02 Nm
■ Moving devices on experiment	None specified
rss running torque disturbance	0.04 Nm

Azimuth torque disturbances, breakfree (bearing reversal)

■ Bearings	0.17 Nm
■ Torque motor	0.04
rss breakfree torque disturbance	0.20 Nm

REQUIREMENTS PLACED ON GONDOLA STRUCTURE

A structural amplification specification is determined based on the stated pointing requirements, the calculated torque disturbances and the known solid body dynamics of the proposed gondola. In various frequency regions this specification places either a velocity limit or a deflection limit on the structure. For the frequency range from 0-4 Hz the structure should act as a rigid body to ensure minimal interaction between the control dynamics and any structural dynamics. Above 4Hz and below 17 Hz the structural requirements can be relaxed to a velocity amplification limit.

At any frequency in this velocity-limited region the requirements on pointing stability can be met if the telescope velocity remains below 33arcsec/sec. Taking into account the deflection of the telescope in solid body rotation due to the known torque disturbances yields a structural transfer function in this range of

$$TFst < 20*w$$

where w is frequency in rad/sec.

This means that any modes that may exist in this range must have an amplitude amplification of less than this function. Thus defined, TFst varies from approximately 500 to 2200.

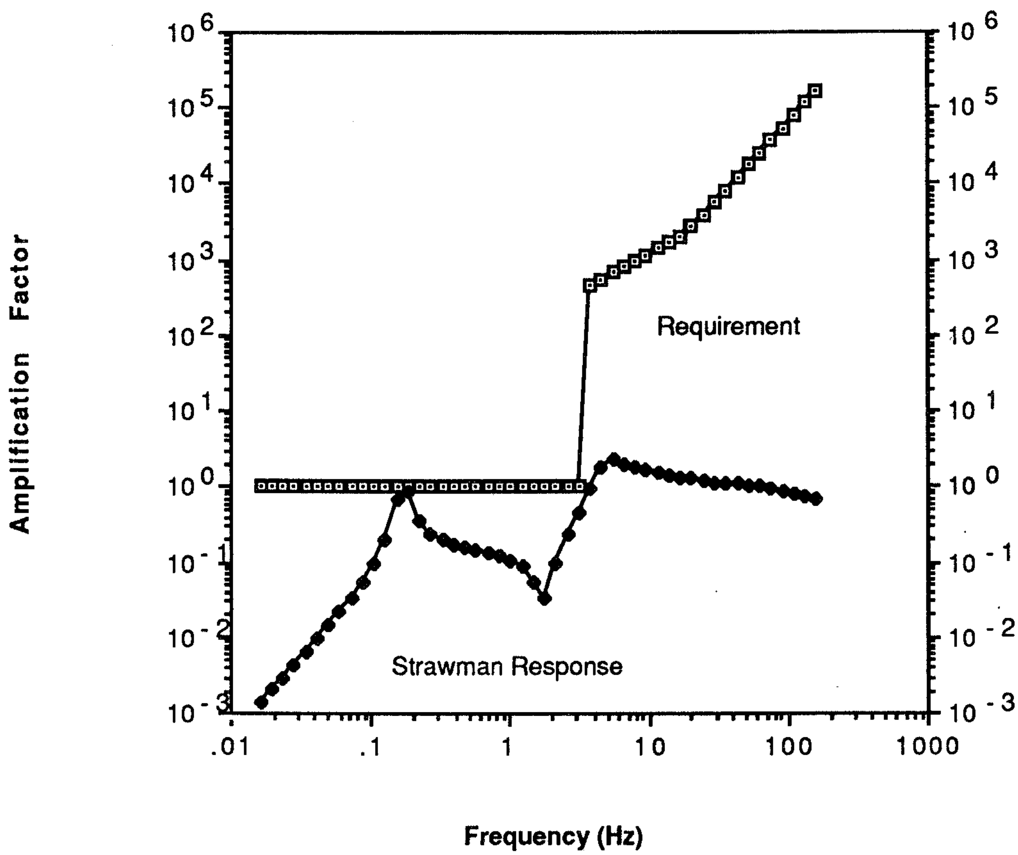
At frequencies above 17Hz the motion requirement can only be met by limiting telescope position changes to less than 0.33 arcsec in 10 ms. Taking into account the solid body rotation of the payload due to estimated torque disturbances, the limiting structural transfer function in this range can be expressed as

$$TFst < 0.17*w^2$$

Any modes that may exist in this range must have an amplitude amplification of less than this function. TFst starts this range at approximately 2170 and rises rapidly.

The composite curve of maximum allowable structural amplification vs. frequency is graphed overleaf superimposed on the predicted frequency response of the strawman structural model.

Strawman Response VS. Requirement



"STRAWMAN" GONDOLA CONCEPT

In order to evaluate the GRID gimbal design in something approaching a real situation, we developed a rudimentary "straw man" model of a gondola which would serve as a structural model for predicting overall system performance. It was designed to meet the weight budget allotted to the GRID experiment package and to approximate the expected stiffness requirements.

The mass inertias of the model were derived and are tabulated on the facing page. In addition, we used our ANSYS structural analysis computer program to predict structural bending modes with 9 degrees of freedom assigned. The seven lowest order modes, their frequencies and descriptions are shown in the following table. Sketches of two representative modes are shown on the facing page.

Mode	Frequency (Hz)	Description
1	3.9	Structure (elevation)
2	4.0	Structure (azimuth)
3	8.6	Structure/Telescope (azimuth)
4	21	Upper structure (bending)
5	21	Upper structure/Telescope (azimuth)
6	24	Lower structure (bending)
7	92	Upper structure (bending)

Note: Elevation bending modes are not shown, as they do not affect azimuth stability.

SAO design concept -- GRID gimbal

"STRAWMAN" GONDOLA -- MASS PROPERTIES

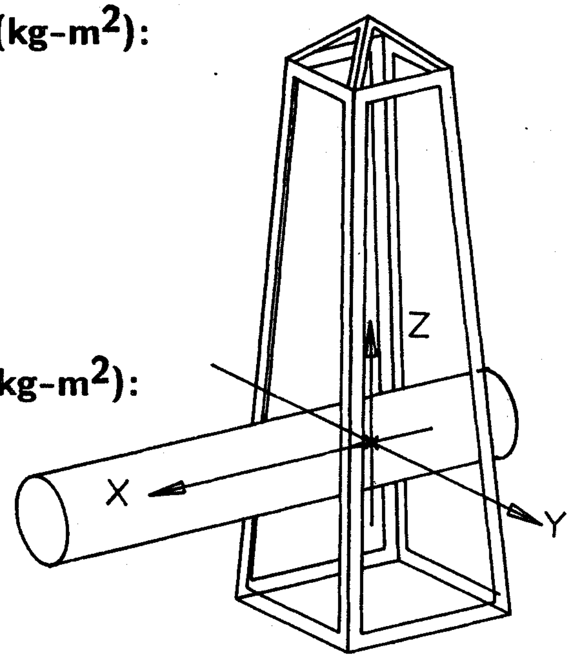
(altitude-azimuth configuration)

Elevation -- mass inertias about the origin (kg-m^2):

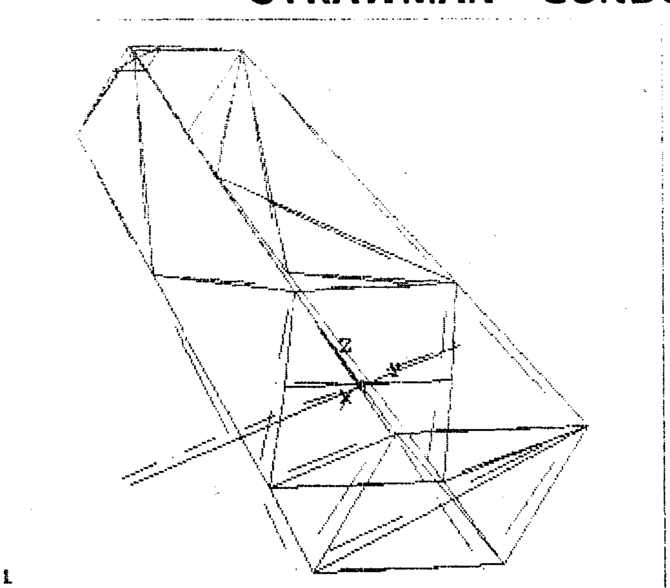
Axes	X	Y	Z
X	177	0	0
Y	0	4840	0
Z	0	0	4839

Azimuth -- mass inertias about the origin (kg-m^2):

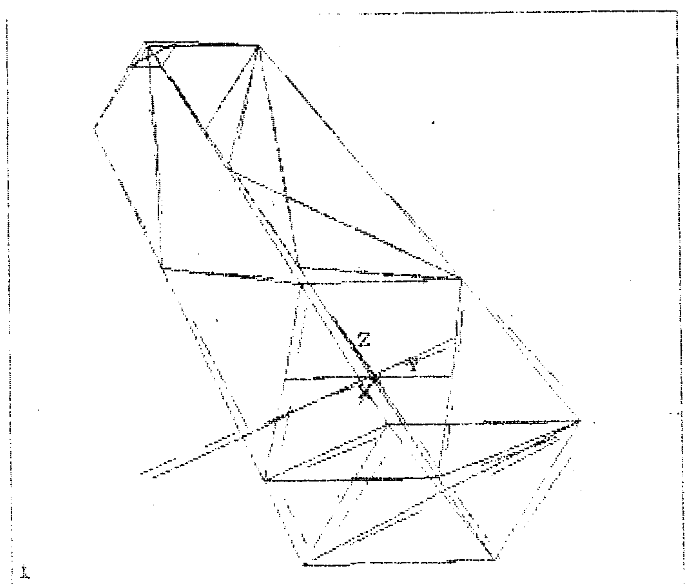
Axes	X	Y	Z
X	5777	0	0
Y	0	10431	16
Z	0	16	5112



"STRAWMAN" GONDOLA -- BENDING MODES



4.01 Hz azimuth mode



8.6 Hz azimuth/telescope mode

hvg.10 -- 4/25/88

ESTIMATED "STRAWMAN" PAYLOAD WEIGHT

The estimated strawman payload weight is shown on the facing page, broken down into contributions from each major subsystem.

The azimuth gimbal bears the weight of all the items listed, except for the parachute and suspension ladder, for a net load of 1560 less 225, or 1335 kg. The elevation gimbal carries only the GRID telescope itself, plus the aspect system, for a net load of 697 kg.

SAO design concept -- GRID gimbal

ESTIMATED "STRAWMAN" PAYLOAD WEIGHT

Item		Estimated weight (kg.)
Gondola frame		164
Gimbal and support system		
Momentum transfer assembly	55	
Reaction wheel assembly	36	
Elevation drive assembly	25	
Magnetometers and gyros	7	
		123
Electronics		
Telemetry, Command and control	11	
Lithium batteries	34	
Enclosures	12	
Miscellaneous (Cables, Connectors, etc.)	17	
		74
Launch and re-entry devices		
Launch lock	7	
Crash pads	18	
		25
Total weight of pointing control		366
GRID experiment		693
Aspect system		4
Total weight of GRID and pointing control		1083
NSBF Equipment		
Ballast	227	
Electronics (CIP)	25	
Parachute and suspension ladder	225	
		477
Total weight beneath balloon		1560
Additional option of cross-elevation system		53
Total (including cross-elevation)		1613

GRID POINTING CONTROL BLOCK DIAGRAM

To complete the system model, we assumed an inner feedback loop using a gyroscope reference, which would be continuously updated by an outer loop referenced to the solar aspect sensor. We also made some assumptions about the bandwidth of each of these loops.

The model was then subjected to simulated step function and broad band torque disturbances, typical of those expected in normal operation. The resulting GRID telescope response is presented here and is shown to lie within the envelope of stated performance requirements.

As shown on the facing page, the pointing control is configured as a gyro-stabilized inner loop with an outer positioning loop referenced to the solar aspect sensor. The inner loop is closed at a frequency which will be some compromise between two undesirable conditions:

1) If the loop bandwidth is made too great, undesirable structural modes may be excited, or

2) If the loop bandwidth is too low, there may be excessive pointing jitter due to bearing and motor torque disturbances.

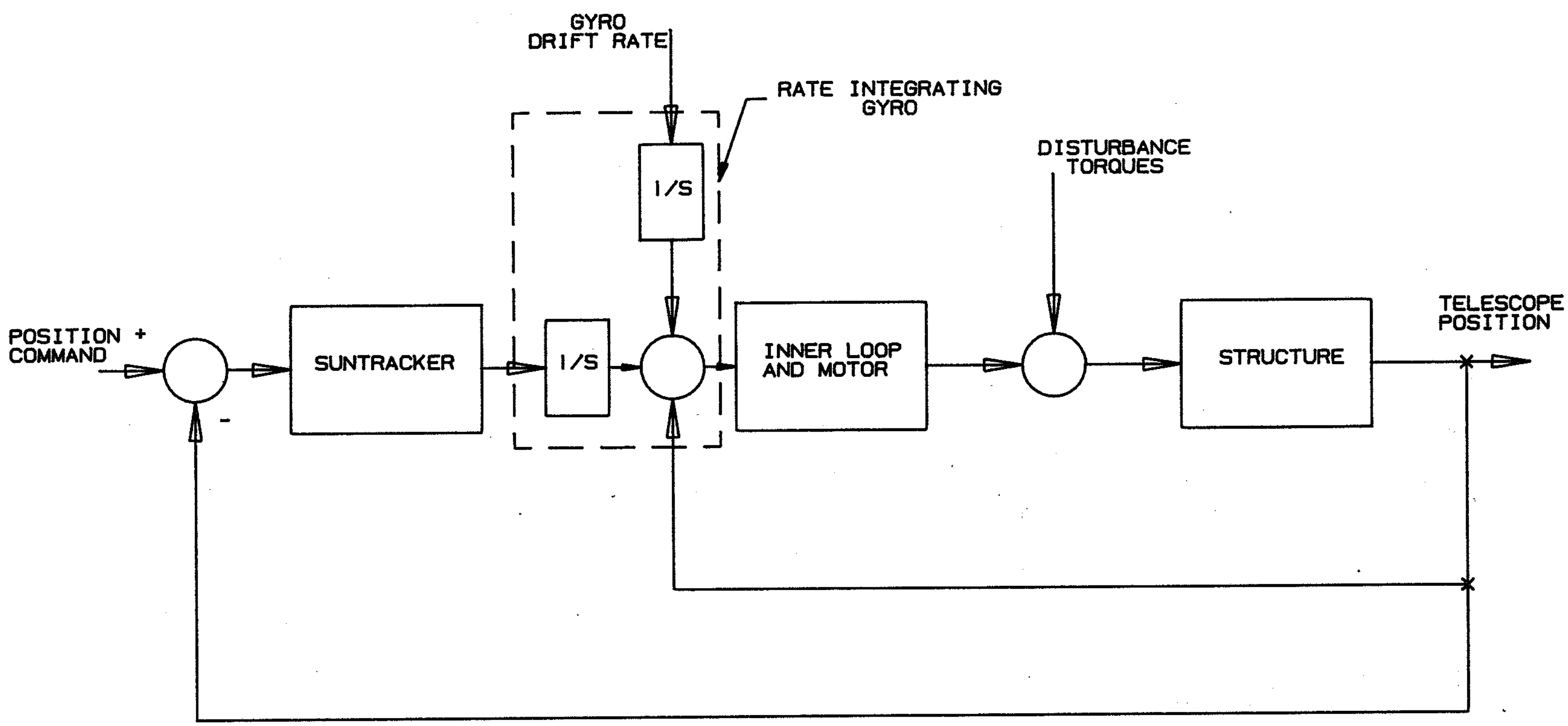
The optimum bandwidth for the inner loop depends on the final gondola design, but will probably lie in the range 0.5 Hz to 2 Hz. The outer loop can be closed at a much lower bandwidth -- say, 0.1 Hz or less -- since it is only required to correct for gyro drifts.

The electronics package required by the gimbal system performs the functions of:

- gyro and sun tracker interfacing
- error signal processing for both inner and outer loops
- loop compensation for inner and outer loops
- torque motor control
- command and telemetry interfacing.

Only one block diagram is shown, since the elevation and azimuth axes are similar, differing mainly in the "structural model" block, and by the addition of a momentum dump system in azimuth.

GRID POINTING CONTROL BLOCK DIAGRAM



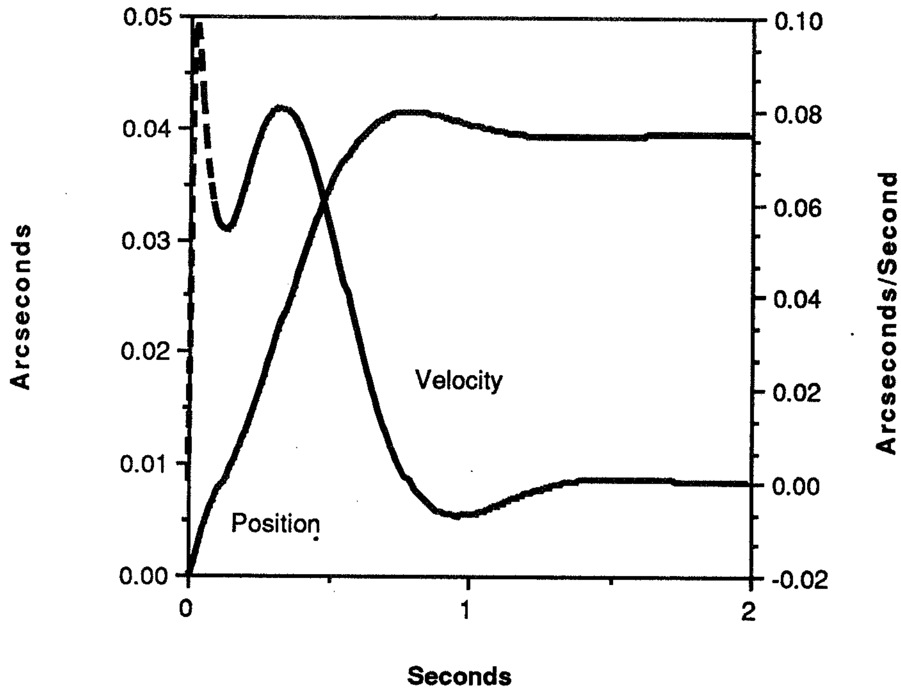
POINTING RESPONSE OF STRAWMAN GONDOLA

The pointing response of the GRID strawman gondola was determined using a model structure and a candidate control law. The structure was designed with weight restrictions in mind, its stiffness and modal response were analyzed and, after stiffening the upper structure, the lowest modes in each axis were moved to 4Hz. This model was placed in a control simulation with a minimum control law of proportional plus rate feedback. The feedback constants were adjusted until the system responded to a step input in under 2 seconds. No further optimization was performed.

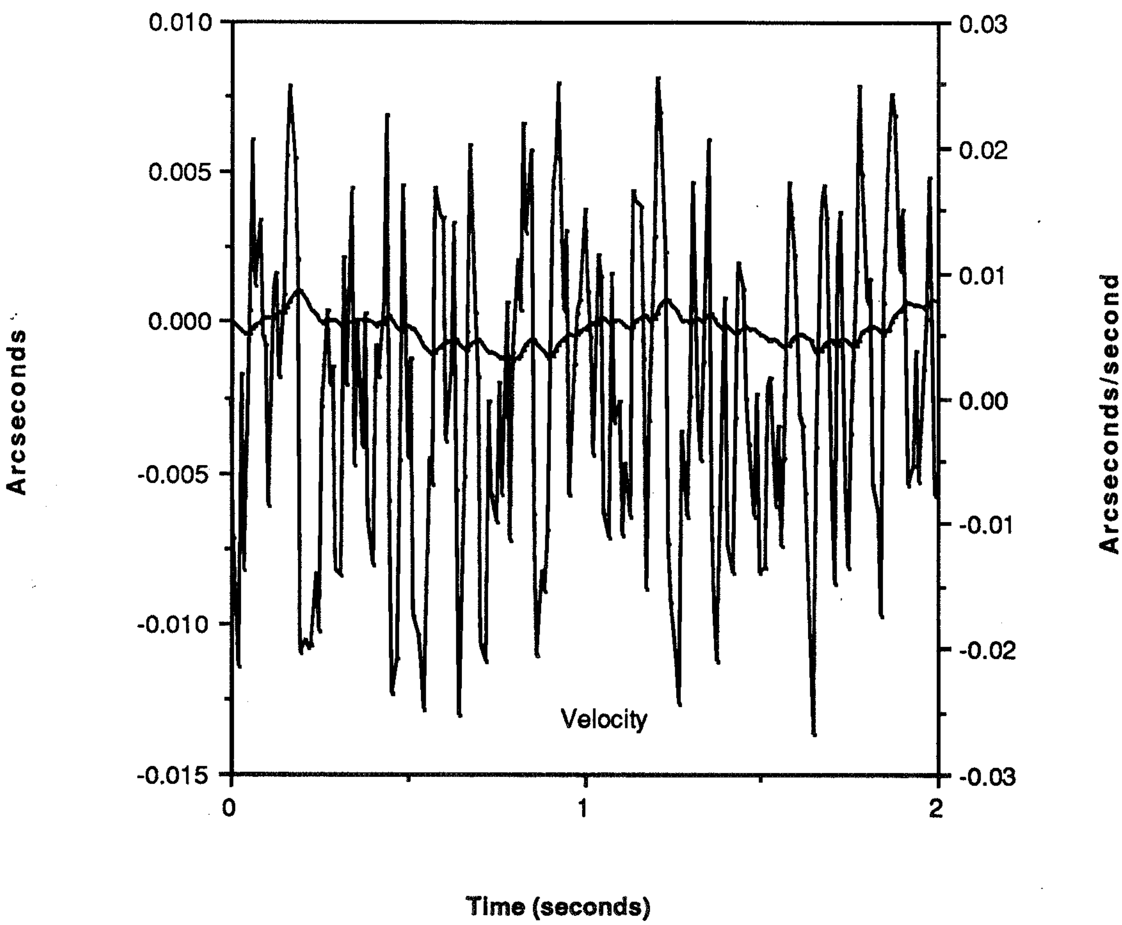
The following page shows the pointing response, in azimuth, of this system. The two graphs show the pointing response to a 0.2 Nm torque step (the estimated break-free torque), and to a random noise disturbance of 0.04 Nm rms (the estimated varying torque disturbance). Both the telescope position and velocity response are shown.

These responses are predicted on the basis of calculated torque noise inputs. These torques result from the bearing friction and are by their nature difficult to predict. Although the actual response may be somewhat higher than we predict here, we do not view this as problem since the modeled response falls below the specified limit of 33 arcsec/sec.

Response to .2Nm Torque Step



Response to .04Nm RMS White Noise

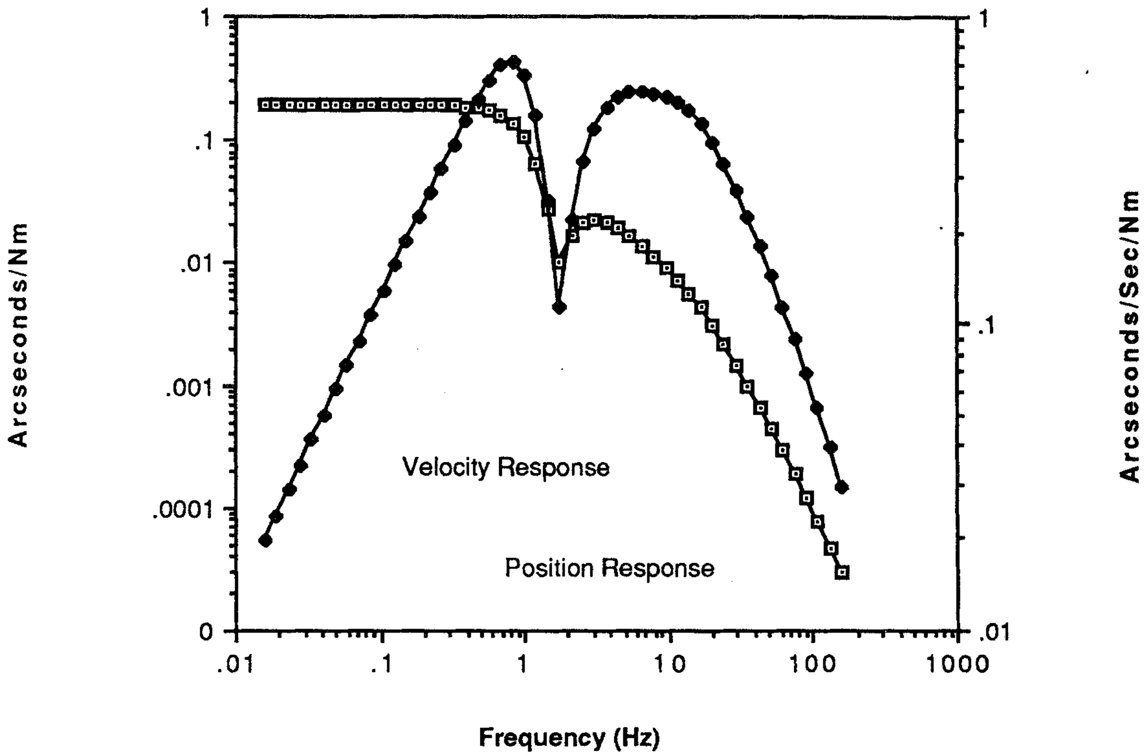


FREQUENCY RESPONSE OF STRAWMAN GONDOLA

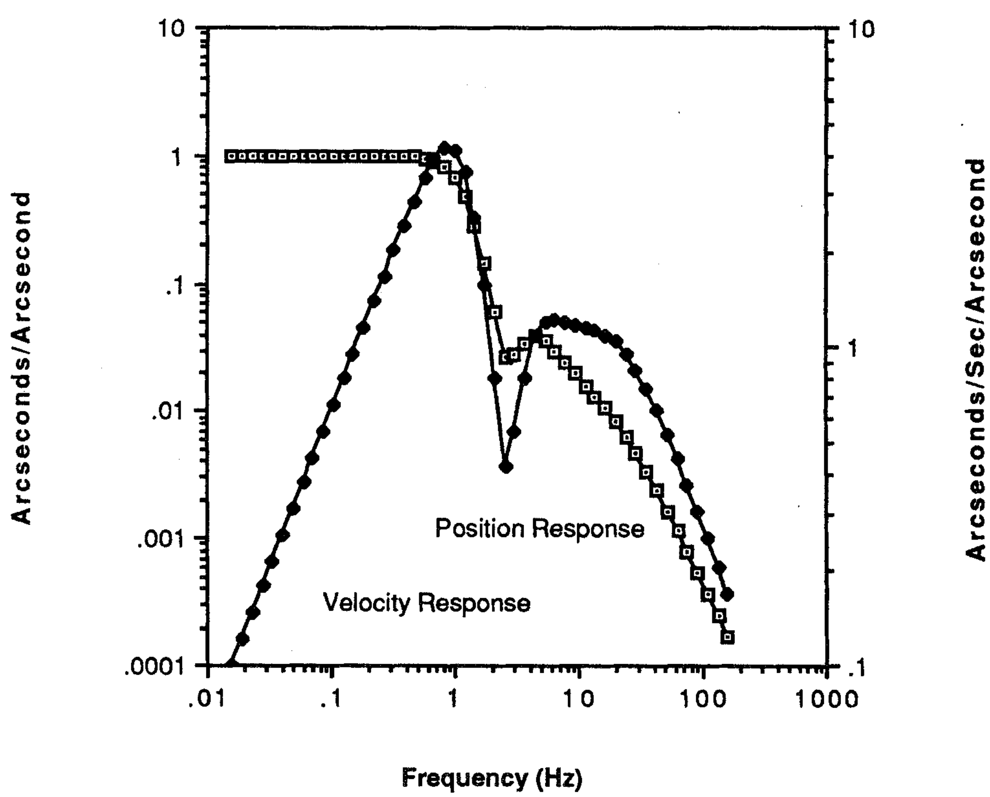
The facing page shows two frequency response graphs. The first shows the telescope position and velocity response to torque noise input at various frequencies. The second shows the predicted response to a position command input.

The peak in velocity response at about 0.6 Hz is caused by loop bandwidth cutoff, and is a natural result of design decisions. The higher-frequency peak clearly shows the effect of structural response, and illustrates the necessity for a properly-damped structure.

Frequency Response to Torque Input



Response to Command Input



SAO design concept -- GRID gimbal

DESIGN TRADEOFFS FOR HIGH ELEVATION ANGLE POINTING CAPABILITY

A. For zenith angles from 23° up to 15°, the balloon obscures the sun at visible wavelengths, causing loss of aspect data

solutions	liabilities
longer suspension ladder (additional 250 ft. required)	increased weight (0.31 kg/ft)
	higher risk of missed launch opportunities, due to more difficult launch procedure
reel down after launch	increased weight
	requires complex mechanism
allow obscuration	requires offset guiding capability (star tracker)
	or; requires very low drift gyro

B. For zenith angles from 15° up to 11°, gimbal lock becomes a problem in addition to obscuration

solutions	liabilities
inner gimbal system (cross-elevation)	increased weight (53 kg)
	additional complexity -- requires another control loop
	requires a suspension ladder or reel down capability as long as 500 ft.

[However, note that an inner gimbal also provides some benefits to the system in the form of increased isolation from the gondola and improved azimuthal pointing capability at all elevation angles.]

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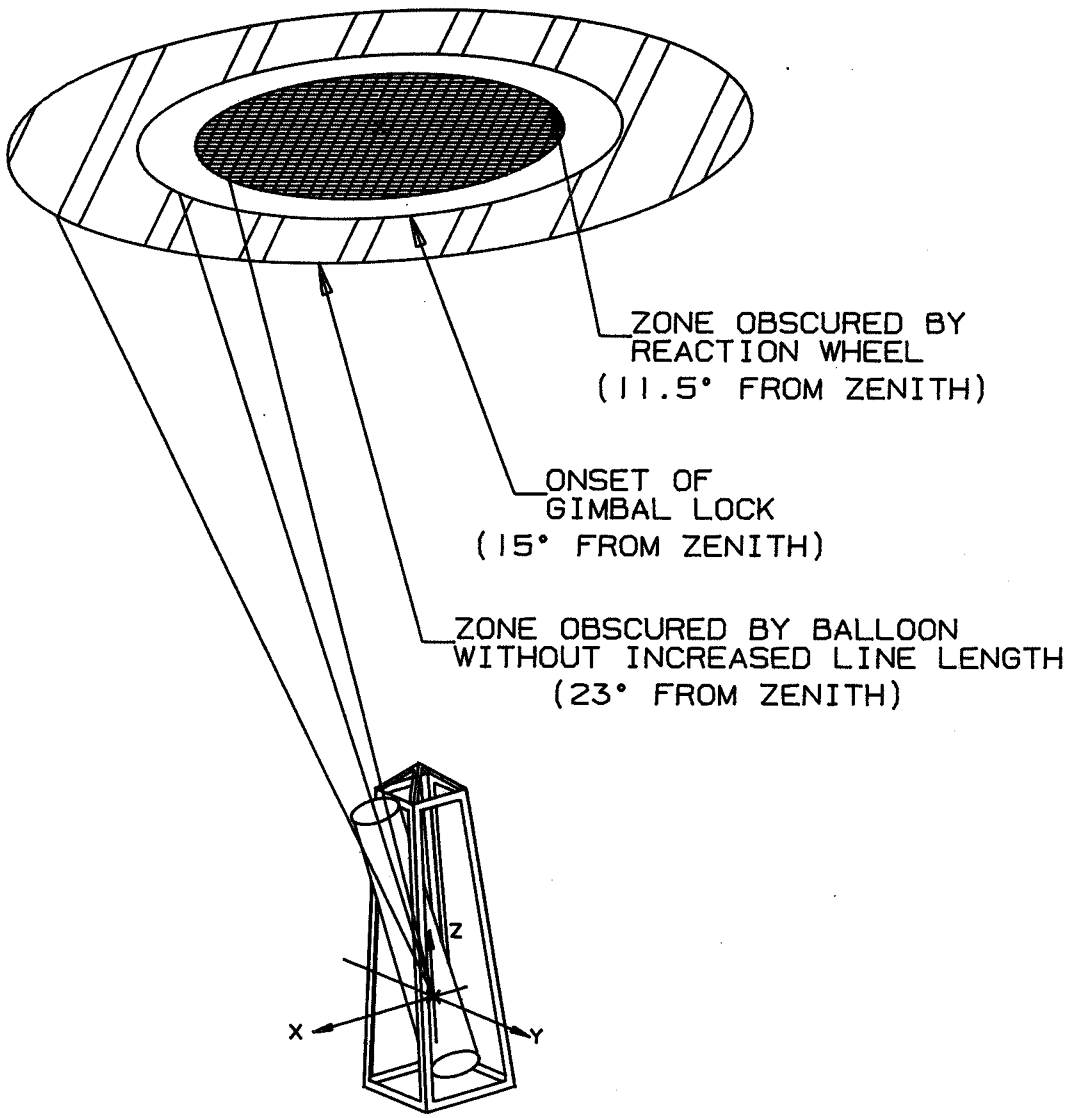


SKY COVERAGE LIMITATIONS
OF THE GRID EXPERIMENT

TELESCOPE OBSCURATION AND OBSERVATION LIMITATIONS NEAR ZENITH

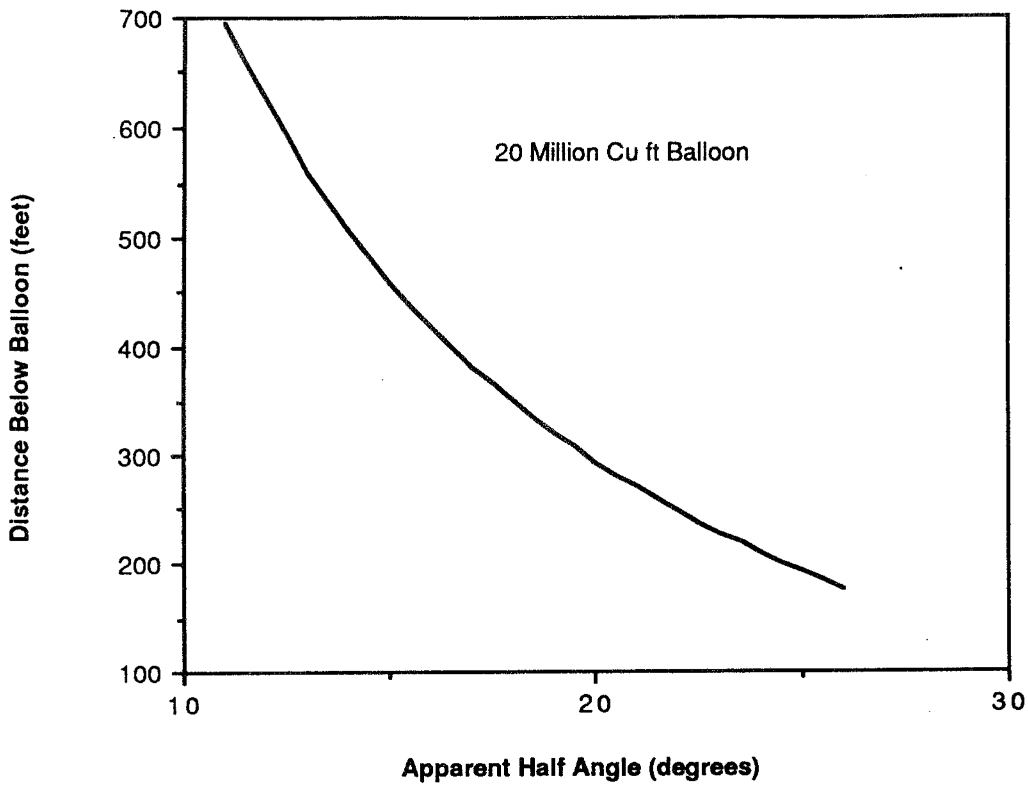
The balloon apparent angle can be reduced by increasing the suspension line length as shown in the graph. The effects of this are:

- Increased payload weight,
- Increased launching difficulty,
- Reduced ability to sink momentum into the support lines.

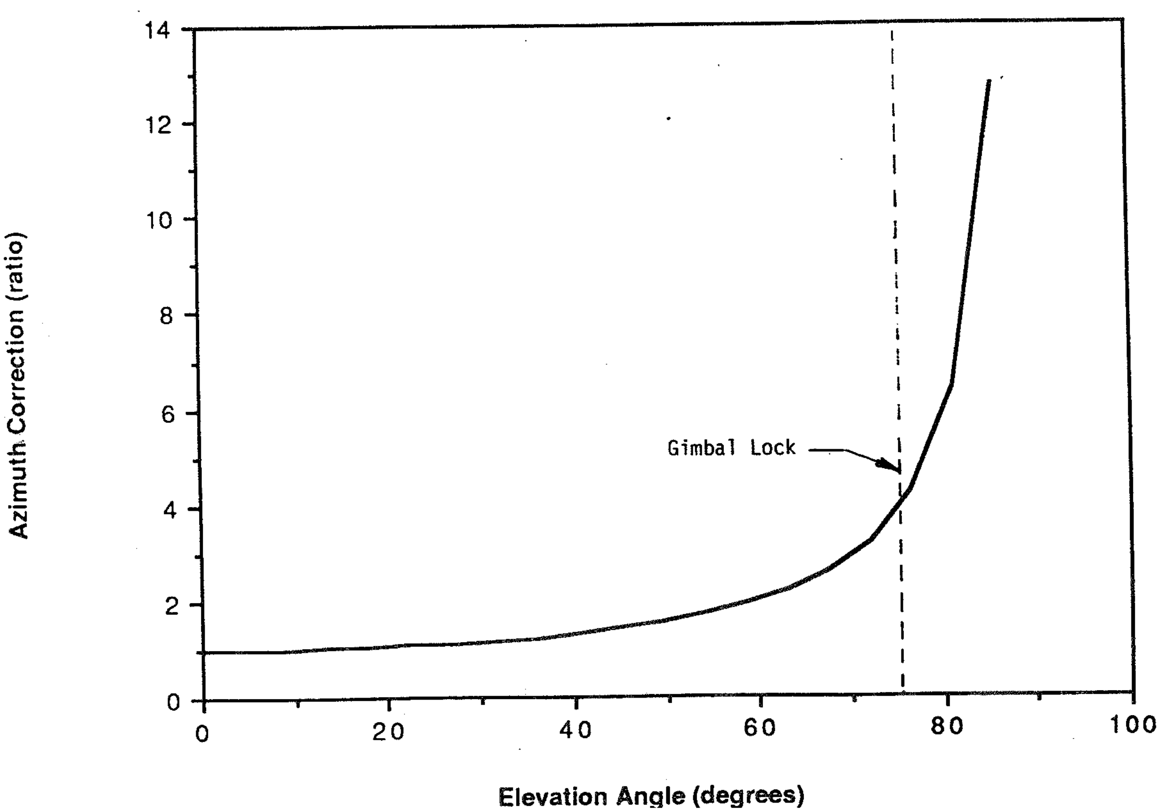
By increasing the difficulty in launch the number of launch opportunities will be reduced. The final effect is due to the fact that as the suspension lines increase in length their apparent stiffness is reduced. This problem can be partially countered by increasing the spacing between the lines, but this causes its own obscuration problem.

If the telescope is used above 75 degrees in elevation (15 degrees away from the zenith) it will start to become uncontrollable due to gimbal lock. This effect can be seen in the second graph on the next page which shows the required azimuth correction for a unit pointing error perpendicular to the elevation axis (that is, in the cross-elevation direction). It increases drastically above 75 degrees, exceeding the available control authority. The gimbal is then said to be locked. A parallel effect is that the azimuth control becomes so violent that it produces disruptive torque noise and reduces the otherwise unaffected elevation pointing performance. This problem could be eliminated entirely by including a second inner gimbal whose axis remains perpendicular to elevation at all elevation angles. This has the secondary advantage of removing the gondola structure from the pointing loop. There is an added weight penalty of about 53 Kg for this second gimbal.

Balloon Obscuration With Added Ladder Length



Azimuth Correction at Given Elevation Angles



SAO design concept -- GRID gimbal

GONDOLA SUPPORT REQUIREMENTS

Steady-state power (30 V d-c batteries)

1) Servo systems, quiescent		100 watts
2) Command and telemetry		20 watts
3) Miscellaneous (heaters, power supply losses, etc.)		40 watts
	Total	160 watts

Transient power (30 V d-c batteries)

1) Servo systems, active 280 watts

Telemetry (16-bit words)

1) 32 analog	(2 second sample period)
2) 4 analog	(0.1 second sample period)
3) 32 digital	(0.1 second sample period)

Commands

Control of the gondola requires about 25% of the standard 16-bit command word space

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GONDOLA SUPPORT REQUIREMENTS

The facing page lists typical support requirements for payloads of this size and complexity, based on our previous experience with balloon gondolas.

Transient servo power is the peak surge that occurs, in addition to the quiescent power, when the gondola or telescope requires maximum correcting torque from the servo systems. In a normal flight, these surges occur only when the telescope is commanded to a new position. Once the telescope has settled at its new position (and any excess momentum dissipated), system power returns to its quiescent level.

Electrical power for scientific balloon experiments is typically supplied by Lithium battery packs in units of 30 amp-hrs at 30 v dc. Several of these can be connected in parallel to furnish any desired energy capacity. The FIRS instrument, for example, is powered in flight by an array of eight battery packs for a total capability of 240 amp-hrs, at 30 v.

Standard NSBF flight support includes a telemetry downlink which handles up to 80 k bits/second of PCM flight data, and a VHF command uplink which transmits 16-bit command words to the gondola. The GRID gimbal/gondola system requires only a small fraction of this capability, leaving the rest available for experiment support.

SAO design concept -- GRID gimbal

ESTIMATED "STRAWMAN" PAYLOAD WEIGHT

Item	Estimated weight (kg.)	
Gondola frame		164
Gimbal and support system		
Momentum transfer assembly	55	
Reaction wheel assembly	36	
Elevation drive assembly	25	
Magnetometers and gyros	7	
		123
Electronics		
Telemetry, Command and control	11	
Lithium batteries	34	
Enclosures	12	
Miscellaneous (Cables, Connectors, etc.)	17	
		74
Launch and re-entry devices		
Launch lock	7	
Crash pads	18	
		25
Total weight of pointing control		366
GRID experiment		693
Aspect system		4
Total weight of GRID and pointing control		1083
NSBF Equipment		
Ballast	227	
Electronics (CIP)	25	
Parachute and suspension ladder	225	
		477
Total weight beneath balloon		1560
Additional option of cross-elevation system		53
Total (including cross-elevation)		1613

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ESTIMATED "STRAWMAN" PAYLOAD WEIGHT

The estimated strawman payload weight is shown on the facing page, broken down into contributions from each major subsystem.

The azimuth gimbal bears the weight of all the items listed, except for the parachute and suspension ladder, for a net load of 1560 less 225, or 1335 kg. The elevation gimbal carries only the GRID telescope itself, plus the aspect system, for a net load of 697 kg.

SURVIVABILITY ASSESSMENT OF THE PROPOSED GRID GIMBAL

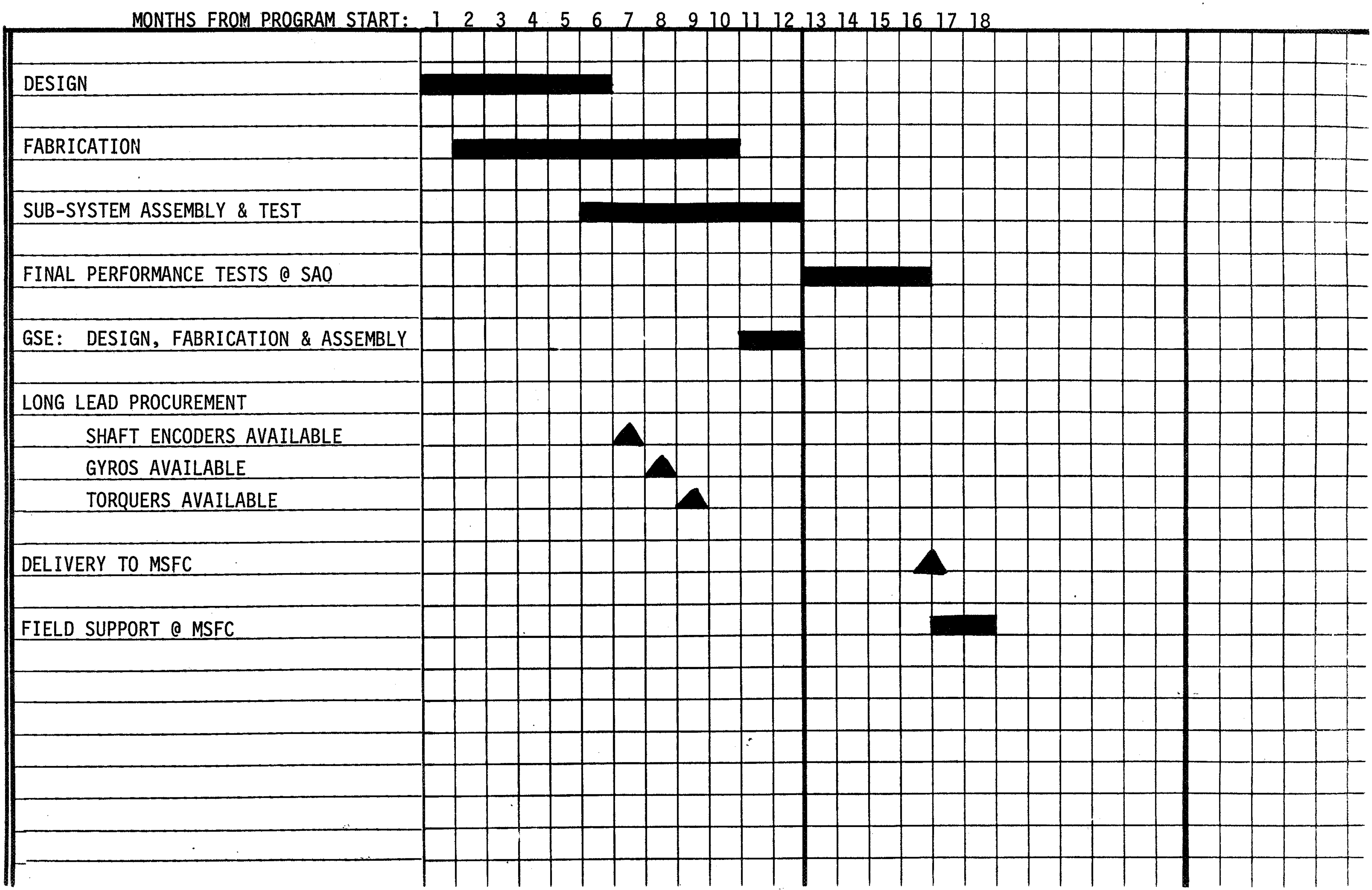
The gondola frame, whose fundamental purpose is to support and position all servo elements, ancillary equipment and the pointed experiment, must also serve as a protective enclosure. Although not shown on the strawman gondola, a key feature contributing to payload protection is the crushable crash rings surrounding the structure. In all twenty of its flights, the 1-meter balloon telescope has sustained only superficial damage to the frame, while none of the servo elements or experiments has ever been damaged.

The GRID gondola frame will be a departure from our previous designs because of payload weight limitations. A carefully optimized frame design is required to carry the GRID experiment through the launch, flight, parachute deployment and landing phases of the mission.

We expect that, on landing, the frame will receive some damage. In that event, it can be either repaired or replaced at a modest cost. The frame, however, will afford about the same level of protection for the GRID experiment, gimbals and auxiliary equipment as our 1-meter balloon gondola.

In summary, we anticipate no damage to the servo elements or the experiment package, and they should be reusable after field servicing.

GRID GIMBAL SYSTEM: MASTER SCHEDULE



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15. Supplementary Notes

16. Abstract

This report studies modification of existing balloon gimbal designs for use on the Gamma Ray Imaging Device experiment. Improved bearings and brushless torque motors are required to lower bearing torque noise and meet stringent pointing requirements. Analytical results from a strawmen gondola and control system design show that pointing requirements are satisfied.

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